Open heavy flavor production at RHIC

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Abstract. The study of heavy flavor production in relativistic heavy ion collisions is an extreme experimental challenge but provides important information on the properties of the Quark-Gluon Plasma (QGP) created in Au+Au collisions at RHIC. Heavy-quarks are believed to be produced in the initial stages of the collision, and are essential on the understanding of parton energy loss in the dense medium created in such environment. Moreover, heavy-quarks can help to investigate fundamental properties of QCD in elementary p+p collisions. In this work we review recent results on heavy flavor production and their interaction with the hot and dense medium at RHIC.

High energy nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) [1] have opened a new domain in the exploration of strongly interacting matter at very high energy density. High temperatures and densities are generated in central nuclear collisions, creating the conditions in which a phase of deconfined quarks and gluons exists (QGP) [2]. The measurements at RHIC in conjunction with theoretical calculations suggest that a dense, equilibrated system has been generated in the collision with properties similar to that of an ideal hydrodynamic fluid. The strong suppression phenomena observed for high-p_T hadrons [3, 4, 5] suggest that the system early in its evolution is extremely dense and dissipative.

Heavy quark (charm and bottom) measurements further expand the knowledge about the matter produced in nuclear collisions at RHIC. Because of their large masses, their production can be calculated by pertubative QCD (pQCD) [6]. In particular, comparative measurements in $p+p$, $d+$Au and Au+Au are sensitive to the initial state gluon densities in these systems [7]. In Au+Au collisions, medium effects such as heavy quark energy loss can be studied through comparison of p_T distributions of bottom and charm production with those observed for inclusive hadrons. The suppression of small angle gluon radiation (dead cone effect) predicted for heavy quarks would decrease the amount of energy loss [8, 9] though gluon emission and, therefore, the suppression of heavy quark mesons at high-p_T is expected to be smaller than that one observed for light quark hadrons at RHIC. In this case, smaller energy loss allows heavy quarks to probe deeper into the medium [10]. It also opens new possibilities to investigate other interaction mechanisms such as collisional energy loss [11, 12, 13, 14, 15] and in medium fragmentation [16]. Moreover, measuring open charm and bottom production at RHIC provides essential reference data for studies of color screening via quarkonium suppression [17].

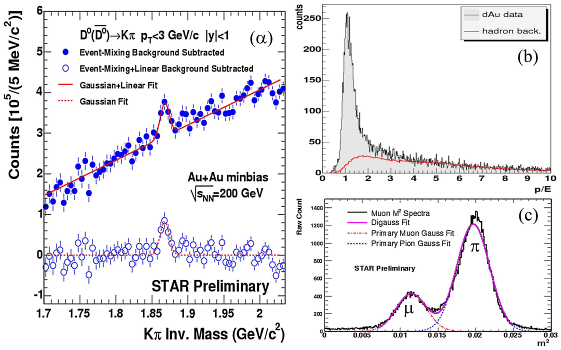

Figure 1. Heavy flavor identification methods used at RHIC. (a) $D^0 \rightarrow K^-\pi^+$ invariant mass spectrum after event mixing subtraction in Au+Au collisions from STAR. (b) p/E spectrum used for electron identification in d+Au collisions from STAR. Similar method is also used by PHENIX. (c) Time of Flight mass spectrum used for muon identification in STAR.

1. Open heavy flavor measurements at RHIC

The study of heavy flavors in relativistic nuclear collisions follows two different approaches: (i) the direct reconstruction of heavy flavored mesons and (ii) the study of semi-leptonic decays of such mesons. In this section we describe these methods, used by STAR and PHENIX, and discuss their advantages and limitations.

1.1. Direct reconstruction of D-mesons

Direct reconstruction of heavy-flavor mesons is being performed by the STAR collaboration using the decay channel $D^0 \rightarrow K^-\pi^+$ (and c.c.) with branching ratio of 3.83% in d+Au and Au+Au collisions. Because of the small branching ratio and the lack of dedicated detector triggers, the direct reconstruction of D-mesons requires the analysis of large amount of data. The available statistics limits the study of such mesons to the low-p_T region ($p_T < 3$ GeV/c). Kaons and pions are identified using the STAR Time Projection Chamber (TPC) dE/dx. The resulting invariant mass spectrum of kaon-pion pairs contains a substantial amount of background from random combinatorics that can be subtracted using mixed event methods. Details of the analysis can be found in Ref [18]. Figure 1-a shows an invariant mass distribution after event mixing subtraction where a clear D^0 peak can be seen.

Despite the limitation on p_T and statistics, direct reconstruction of D-mesons is the cleanest probe to investigate heavy quarks in relativistic nuclear collisions.

1.2. Semi-leptonic decays of D and B mesons

Direct reconstruction of D-mesons can be done only by STAR in a limited p_T range and still difficult to perform with high efficiency in high multiplicity events. In this case semi-leptonic decays of such mesons (Ex: $D^0 \rightarrow e^+ + K^- + \nu$) provide a more efficient measurement of charm and bottom production. At RHIC two methods are utilized to measure heavy flavor production via semileptonic decays: (i) identification of electrons from D and B-meson decays and (ii) identification of muons from D-meson decays.

The analysis of non-photonic electrons (the excess of electrons after subtracting all possible sources of background, such as photon conversions and Dalitz decays) is a technique used by STAR and PHENIX. Electron identification in STAR is done using the dE/dx and momentum (p) information from the TPC and the Time of

Flight (ToF) data for low-p_T ($p_T < 4 - 5$ GeV/c) electrons [18] or energy (E) and shower shape in the electromagnetic calorimeter (EMC) for high-p_T ($p_T > 1.5$ GeV/c) electrons [19] (see Figure 1-b).

Electron identification in PHENIX [20, 21] is largely based on the Ring Imaging Cherenkov detector (RICH) in conjunction with a highly granular EMC. The momentum is derived from drift and pad chambers.

A major difficulty in the electron analysis for both experiments is the fact that there are many sources of electrons other than semi-leptonic decays of heavy-flavor mesons. The main sources of background are photon conversion in the detector material (less significant in PHENIX due to the reduced amount of material when compared to STAR) and π^0 and η Dalitz decays. Other sources of background, such as ω, ϕ and ρ decays are also taken into account, although their contribution is small compared to the sources mentioned above. These background sources are commonly called photonic electrons.

Background subtraction in the PHENIX experiment is performed by two different methods: (i) The converter method, in which a well defined amount of material is added to the detector to increase the number of background electrons. By comparing the electron spectra with and without the converter it is possible to measure directly a significant part of the background. (ii) The cocktail method, with which PHENIX measures the spectra of the main background sources (photons, π^0 and η). Both methods agree to each other very well.

Due to its the large acceptance and tracking efficiency, STAR can directly reconstruct a considerable fraction of the photonic background by performing invariant mass reconstruction of e^+e^- pairs with high efficiency. For photon conversion, π^0 and η Dalitz decays the invariant mass spectrum shows a peak near zero mass. Other background sources are evaluated by simulations and account for a very small fraction of the total background in this case.

Muon identification at low-p_T ($p_T < 0.25$ GeV/c) plays an important role because this p_T range imposes a significant constrain on the measurement of charm cross section [22]. This measurement is being done by STAR using dE/dx and momentum information from the TPC and mass reconstruction from the ToF detector. A clear muon signal can be reconstructed, as seen in Figure 1-c. Background from π and K decays can be subtracted by looking at the DCA (distance of closest approach) between the muon and the primary vertex of the collision.

2. Charm production at RHIC

The determination of the total charm cross section via non-photonic electrons requires precise measurements down to very low-p_T. This is an experimental challenge: the lower the p_T, the higher the amount of photonic electrons that contaminates the measurement, resulting in large systematic uncertainties. In order to overcome this limitation STAR performs three independent measurements: direct reconstruction of D-mesons, μ and $e^\pm$. The total charm cross section is obtained from a combined fit of these measurements [22] as illustrated in Figure 2-a. PHENIX, on the other hand, uses its $e^\pm$ measurements to extract total cross sections [21]. To overcome the large background at low-p_T PHENIX is improving analysis techniques in order to reduce systematic uncertainties due to photonic background. This allowed a decrease in the minimum p_T that can be measured by PHENIX from ~ 0.8 in the earlier datasets to ~ 0.4 GeV/c (Figure 2-b).

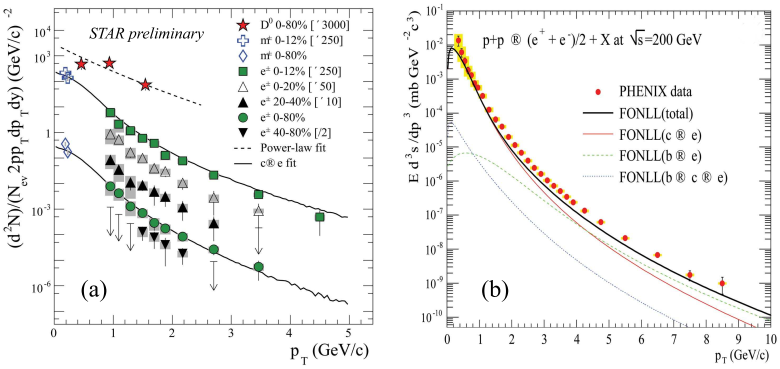

Figure 2. Data used by STAR and PHENIX to study total charm production at RHIC. (a) D^0, μ and electron data used in a combined fit from STAR. (b) electron data used by PHENIX. Curves are FONLL prediction used by PHENIX to extrapolate the electron spectra to $p_T = 0$.

Figure 3-a summarizes all charm cross section measurements from p+p to central Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV at RHIC [18, 20, 21, 22, 23]. Shown is the total cross section per binary collision. Figure 3-a makes evident a factor of ~ 2 between STAR and PHENIX, this difference being larger than the combined systematic uncertainties in the case of central Au+Au collisions. The dashed line in this figure depicts the average prediction from FONLL calculations [24] for charm production at RHIC energies and the yellow band its uncertainty determined by independent variation of quark masses, renormalization and factorization scales. The dash-dotted lines correspond to the average values for both experiments. Despite the differences between experiments the results, for each experiment, suggest that charm production follows a binary scaling from p+p to central Au+Au collisions. This is a strong indication that charm are predominantly produced in the early stages of the collision evolution and other processes, such as thermal production in the QGP, are not significant.

Figure 3-b shows the ratio of STAR [19] and PHENIX [21] measurements to FONLL calculations for high-p_T electrons in p+p collisions at RHIC. The dash-dotted lines correspond to the ratio of the experimental to FONLL cross section. This makes evident that the factor of ~ 2 discrepancy in the cross section extends up to large p_T values. Note that, despite this normalization discrepancy FONLL describes the shape of the measured spectra well in both cases, suggesting that the differences between the measurements may be related to an experimental normalization effect.

Future RHIC measurements will address this experimental discrepancy. STAR is planning a run without its inner tracking detectors (SVT and SSD) in the next years thus reducing the amount of photon conversion and will address in detail some of the systematic uncertainties in the background removal of the electron measurements. Added to that, both STAR and PHENIX are developing detector upgrades providing drastic improvements in secondary vertex reconstruction which will allow the use of displaced vertex techniques to direct measure D and B mesons with high precision and efficiency.

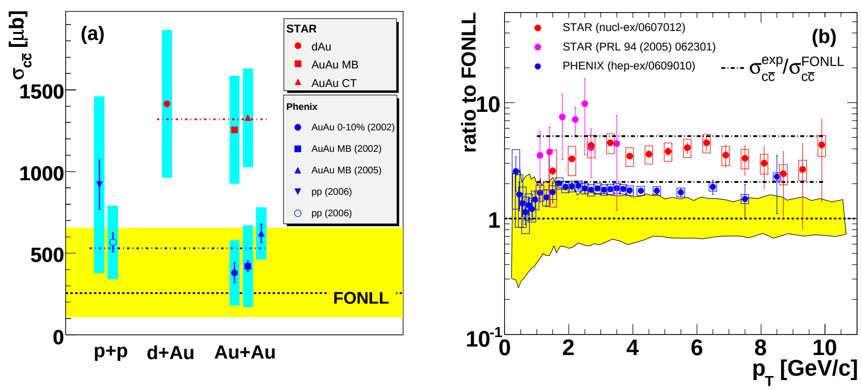

Figure 3. (a) Overview of the experimental charm cross section at RHIC from p+p to central Au+Aucollisions. (b) ratio of measured non-photonic electron yield to FONLL pQCD calculations for p+p collisions.

3. Modifications of heavy flavors in the medium

Putting aside the discrepancies in the absolute cross sections measurements between STAR and PHENIX we now investigate how heavy quarks interact with the QGP formed in Au+Au collisions at RHIC. Over the last few years RHIC is providing interesting information on how the partons behave in such hot and dense medium. The study of flavor dependence of these interactions will further expand our knowledge about the properties of the nuclear matter under such extreme conditions.

3.1. Energy loss of heavy quarks

Nuclear effects in non-photonic electron production are measured through the comparison of spectra from d+Au and Au+Au collisions to the equivalent spectrum in p+p: the relevant quantity is the ratio $R_{AA}(p_T) = (dN_{AA}/dp_T)/(T_{AA} \times dN_{pp}/dp_T)$, where dN_{AA}/dp_T is the differential yield in Au+Au (d+Au) and dN_{pp}/dp_T the corresponding yield in p+p collisions. T_{AA} is the nuclear overlap integral, derived from Glauber calculations [25]. In the absence of nuclear effects, such as shadowing, Cronin effect, or gluon saturation, hard processes are expected to scale with the number of binary collisions and hence, $R_{AA}(p_T) = 1$. Figure 4-a shows the average R_{AA} for high-p_T non-photonic electrons as a function of $N_{\rm part}$ for STAR and PHENIX data. Despite the cross section discrepancies between STAR and PHENIX, R_{AA} results are consistent with each other. R_{AA} for non-photonic electrons shows an increasing suppression from peripheral to central Au+Au collisions, indicating an unexpectedly energy loss of heavy quarks in the medium. This suppression is similar to the one observed for light-quark hadrons, indicated by the shaded area in the figure. For the 5% most central collisions, non-photonic electron production for $p_T > 6$ GeV/c is suppressed by a factor ~ 5.

The suppression of non-photonic electrons in central Au+Au collisions can be, to some degree, explained in terms of radiative energy loss in the medium. Figure 4-b also shows different theoretical predictions for the non-photonic electron suppression in central Au+Au collisions considering different energy loss mechanisms. Curves (I)

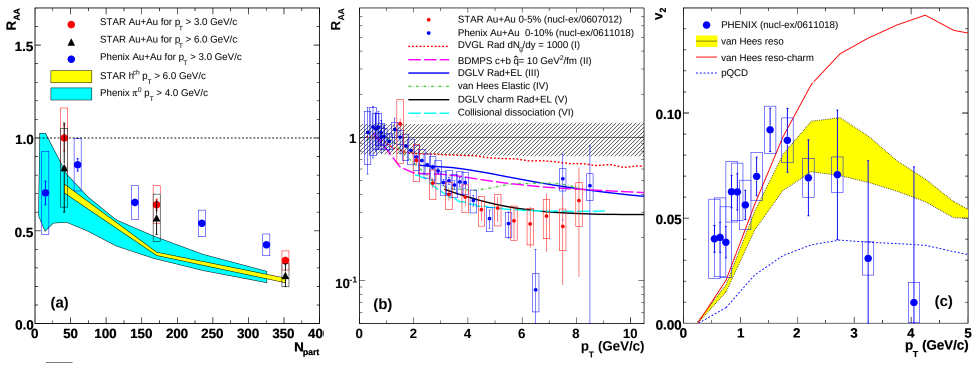

Figure 4. Modification of non-photonic electrons in Au+Au collisions at RHIC. (a) R_{AA} as a function of $N_{\rm part}$ (b) R_{AA} as a function of p_T for central collisions (see text). (c) v_2 as a function of p_T for minimum bias collisions.

and (II) correspond to the expected heavy quark suppression when the energy loss mechanism is induced gluon radiation, considering electrons from D and B mesons decays. Curve (I) corresponds to the average value of DVGL radiative energy loss calculation in which the medium gluon density is $dN_g/dy = 1000$ [12]. In this case, the radiative energy loss does not account for the observed suppression, although the uncertainties, both in the data and theory, are large. On the other hand, Curve (II) [13] shows a larger suppression than Curve (I). In this case, however, the sensitivity of R_{AA} to the time averaged transport coefficient $\hat{q}$ becomes smaller as it increases. In fact, the variation in R_{AA} for $4 < \hat{q}$ (GeV^2/fm) < 14 at $p_T > 3$ GeV/c is only ~ 0.15 [13]. This saturation of the suppression for high values of $\hat{q}$ can be attributed to the highly opacity of the medium, biasing the particle production towards its surface. Although gluon radiation is still expected to be a significant energy loss mechanism other processes may become important to describe the suppression observed in central Au+Au collisions. Curve (III) is an average prediction for electrons from heavy-quark mesons decays and includes both DVGL radiative and elastic energy loss, as well as jet path length fluctuations [14]. In contrast with light quarks, the elastic energy loss is comparable to the radiative for heavy quarks [11] and the effect on R_{AA} is significant. In fact, theoretical predictions for elastic rescattering of partons in the medium that can create resonant D and B meson states via quark coalescence [15] in the medium can lead to a significant suppression at moderate p_T as seen in Curve (IV). In this case, the amount of suppression depends on the resonance widths. Other processes, such as in-medium fragmentation [16], shown in Curve (VI) may also contribute to the observed suppression in central Au+Au collisions. It is clear that the full understanding of the energy loss mechanisms is a fundamental milestone for the characterization of the medium properties. Heavy flavors provide an important tool to investigate these mechanisms.

3.2. Elliptic flow of heavy flavors

It has been argued that the matter created in heavy-ion collisions at RHIC is sufficiently hot and dense that charm quarks might thermalize in the medium [26]. The most promising method to study this hypothesis is the measurement of charm elliptic

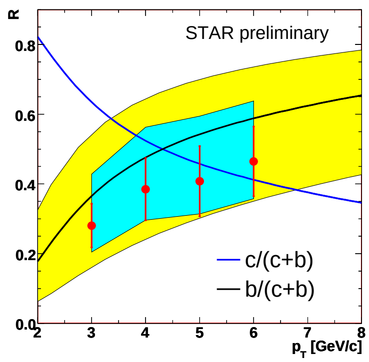

Figure 5. Preliminary results on the relative contribution of B meson decays to the non-photonic electron spectra in p+p collisions at RHIC [27].

flow. Large elliptic flow for D-mesons would imply in a large number of interactions, enough to suggest thermalization.

Recent PHENIX results [20] for non-photonic electron v_2, shown in Figure 4-c, suggest that charm quarks carry a substantial amount of v_2. Non-photonic electron v_2 at low-p_T is compatible with rescattering+resonances calculations suggesting a reduction in thermalization times of heavy quarks in the medium, when compared to pQCD scattering [15]. At high-p_T we notice a tendency of dropping in the non-photonic electron v_2, although the statistical uncertainties are very large. This could be an indication of increasing dominance of electrons from bottom productions since bottom is not assumed to show a pronounced v_2. More precise data and the independent measurement of D-meson v_2 is fundamental to understand v_2 in this p_T region.

4. The next step: D and B mesons contributions to semi-leptonic measurements

Generally, all current models overpredict R_{AA} at high-p_T. It is important to note that in all calculations charm quarks are substantially more quenched than bottom quarks. Curve (V) in Figure 4-b, which is based only on electrons from D decays describes the data best. It is the dominance of electrons from B decays for $p_T > 4 - 5$ GeV/c that pushes the predicted R_{AA} to higher values. All theoretical calculations use the relative contribution of D and B as predicted by pQCD calculations [24]. The understanding of the observed suppression as well the observed v_2 of non-photonic electrons require independent measurements of D and B mesons at high-p_T.

$e - h$ $\Delta\phi$ correlations in p+p collisions is a promising tool to measure this relative contribution. In general, heavy flavors have harder fragmentation functions than gluons and light quarks, making the near side correlation ($\Delta\phi \sim 0$) more sensitive to the decay kinematics. Figure 5 shows preliminary data from STAR on the relative contribution of charm and bottom to the non-photonic electron data. The relative contribution is obtained from the fit of the near side correlation with predictions for $e - h$ correlations for D and B mesons from Pythia. Experimental uncertainties contain the ones from photonic background removal (dominant part) and the choice of fit method. Details of this analysis can be found in Ref [27]. The lines show FONLL predictions for charm and bottom. The yellow band reflects the uncertainty in the calculation. Within errors, the experimental data is compatible with FONLL calculations. This result, if confirmed, would imply that bottom may be more suppressed in central Au+Au collisions than predicted by current energy loss calculations. In order to further investigate the relative contribution of charm and bottom to non-photonic electrons one may look for $e-D^0$-meson correlations at $\Delta\phi\sim\pi$ in p+p collisions. Because of the decay channels of D and B mesons the study of the charge dependence ($e^- - D^0$ and $e^+ - D^0$) of this correlations can help on the separation of electrons from $c\bar{c}$ and $b\bar{b}$ pairs.

5. Final remarks

RHIC is providing challenging data on heavy flavor production and its interplay with the medium. Recent results show that this interaction with the medium is stronger than what we expected resulting in a large energy loss in central Au+Au collisions. In order to take the next step it is imperative to independently measure nuclear modification factors and v_2 of D and B mesons. This will be possible in the near future when detector upgrades are available. Detailed and systematic measurements are required to address existing discrepancies and are fundamental to our understanding of heavy flavor production at RHIC.

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